



Research Paper

Influence of baffle configurations on flow and heat transfer characteristics of unilateral type helical baffle heat exchangers

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HIGHLIGHTS

- Unilateral ladder type helical baffle heat exchangers (ULHBHXs) were investigated.
- Main and leakage flow patterns were depicted on slices in half cylindrical space.
- Impacts of baffle pitches and incline angles on performances were discussed.
- Performances of all helical baffle schemes are higher than those of segmental ones.
- ULHBHX with plane Baffle A has highest comprehensive indexes in the studied scope.

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ABSTRACT

The flow and heat transfer performances were investigated on unilateral ladder type helical baffle heat exchangers (ULHBHXs) with different geometrical structures in half cylindrical space and compared with those of the segmental baffle heat exchangers (SBHXs). The unilateral ladder type helical baffles consist of two alternate groups of plates, the folded baffles (Baffles A) and the segment ones (Baffles B). The studied ULHBHXs include the combination schemes of different Baffle A with different baffle pitches (40, 60, 80 mm) and different projection length of inclined section ($l = 60, 72, 84$ mm and a plane one). Visualization methods of nephograms were adopted on special slices to clearly reveal the impacts of baffle configurations on flow patterns. The numerical results show that the shell-side heat transfer coefficients of the ULHBHX schemes with folded Baffles A are superior but the comprehensive indexes are inferior to those of the corresponding plane ones, and all the helical schemes are superior to those of the segmental schemes. The average ratios of shell-side heat transfer coefficient, pressure drop and comprehensive indexes $h_o \Delta p_o^{-1}$ and $h_o \Delta p_o^{-1/3}$ of all the twelve ULHBHX schemes over those of the SBHX ones with corresponding baffle pitches are 1.166, 0.670, 1.851 and 1.352, respectively.

1. Introduction

Robust and flexible shell-and-tube heat exchangers (STHXs) are widely used in various industrial processes such as power stations, petroleum refineries, refrigeration, food and chemical plants, etc. The U-tube STHXs are one of important types of STHXs which can withstand even higher temperature/pressure conditions with their less thermal stress free end structure. For example, high-pressure feedwater heaters are the U-tube STHXs used in power plants to preheat the feedwater by extraction steam from steam turbines. It is of great importance to improve their heat transfer performance, especially for the shell-side, which is critical to increase overall system efficiency [1–4].

The configuration and structure of the baffles supporting the tube bundle inserted in the shell are crucially important for the performance

of STHXs. Segmental baffles are commonly used to guide the flow for the heat transfer, while the zigzag flow pattern unavoidably results in dead zones at the corners of each baffle and inner shell wall that decrease the heat transfer coefficient and induce vibration and fouling. Lutchka and Nemcansky [5] firstly proposed quadrant helical baffle heat exchangers (HBHXs) that demonstrated good thermo-hydraulic performance, low vibration level and anti-fouling. Then various improved methods have been investigated numerically or experimentally pertaining to helical baffles in substitution of segmental ones [6–10]. Chen [11] proposed the trisection HBHXs to suit the most popular equilateral triangle tube layout and Chen et al. [12,13] proposed and investigated the circumferential overlap trisection HBHXs by widening the straight edges of the sector baffles to accommodate one or two rows of tubes in the circumferential overlap area of the adjacent baffles, and the

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Nomenclature*Latin letters*

A	heat transfer area, m^2
a	tube pitch, m
c_p	specific heat, $\text{J kg}^{-1} \text{K}^{-1}$
D_s	inner diameter of shell, m
d	diameter of tube, m
h	heat transfer coefficient (h.t.c.), $\text{kW m}^{-2} \text{K}^{-1}$
K	overall heat transfer coefficient, $\text{kW m}^{-2} \text{K}^{-1}$
k	turbulence kinetic energy, $\text{m}^2 \text{s}^{-2}$
L	effective length of tube, m
l	projection length of the inclined section, m
m	mass flow rate, kg s^{-1}
P	helical pitch, m
p	pressure, kPa
Pr	Prandtl number
Q	heat, kW
$Re_{z,o}$	axial Reynolds number
S_ϕ	generalized source term
T	temperature, K
U	velocity vector, m s^{-1}

u	velocity component in the x direction, m s^{-1}
v	velocity component in the y direction, m s^{-1}
w	velocity component in the z direction, m s^{-1}

Greek letters

Γ_ϕ	generalized diffusion coefficient
Φ	universal variable
β	incline angle of baffle $^\circ$
Δ	difference
δ	thickness of baffle, m
ε	turbulence kinetic energy dissipation rate, $\text{m}^2 \text{s}^{-3}$
λ	thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
μ	dynamic viscosity, N s m^{-2}
ν	kinematic viscosity, $\text{m}^2 \text{s}^{-1}$
ρ	density, kg m^{-3}

Subscript

i	tube-side
o	shell-side
in	inlet
out	outlet

experimental and numerical results showed that the heat transfer performance was significantly improved. Dong et al. [14] numerically compared four shapes or connection configurations of baffles with identical helix pitch of trisection helical baffle heat exchangers. The results showed that the trisection circumferential overlap scheme performed the best for well restraining the shortcut leakage at triangle zones between adjacent baffles in contrast to the other schemes. Dong et al. [15] and Wang et al. [16] presented and investigated the trisection circumferential overlap heat exchangers with folded circumferential overlap baffles for restricting leakage and convenient manufacture and installation. Tang et al. [17] investigated the performances of axial separation helical baffle heat exchangers which can facilitate variation of baffle incline angle for reducing the manufacture cost. Moreover, many novel types of helical baffle heat exchangers also have been proposed by changing baffle shapes or connection configurations to enhance the performance. Du et al. [18] put forward a sextant helical baffle heat exchanger using quadrant baffles and indicated that the shortcut leakage flow can be reduced by circumferential overlapped baffles. Wen et al. [19] proposed a ladder-type folded baffle scheme with the same intention to block the leakage zones of the HBHXs, the numerical results showed that the shell-side fluid flow is more close to the spiral flow with circumferential overlapping adjacent baffles, thus the shell-side heat transfer of the heat exchanger can be improved. And Wen et al. [20] also experimentally investigated the shell-side velocity field and distribution of folded sector-shaped plain baffle heat exchangers by particle image velocimetry (PIV), and the results show that the smaller axial velocity and higher radial velocity are beneficial to heat transfer with a small pressure loss.

The optimal incline angle or helical angle of helical baffle heat exchangers has been widely studied since it is of great thermodynamic concern in designing shell and tube heat exchangers. Chen et al. [21] conducted performance tests on both oil-water and water-water heat transfer of five small incline angle heat exchangers and the results show that there is no need to pursue large incline angle if the flow rate at shell side is small. Wang et al. [22] studied trisection circumferential overlapped baffles with incline angles of 20°, 25° and 30° for shell-side flow, and the simulation results showed that the optimal incline angle of helical electric heater is 25°, which has both the highest comprehensive index and relatively high heat transfer coefficient. Lei et al. [23] simulated and discussed seven baffle incline angles, and the results

showed that the effect of incline angle on pressure drop was very small when incline angle was greater than 40°, while the variation of the pressure drop was relatively large for small incline angle. Saeedan and Bahiraei [24] used two-objective optimization to analyze the effects of helix angle and baffle axial overlapping, and the results indicated that heat transfer and pressure loss decrease with the increase in both the helix angle and the amount of baffle overlapping. Gao et al. [25,26] experimentally studied the effects of five helix angles of 8°, 12°, 20°, 30°, 40° on the irreversibility in discontinuous helical heat exchangers, and confirmed that the comprehensive performance of HBHX with 40° helix angle being the highest among the five testing schemes. Nemati Taher et al. [27] studied impact of baffle space (1/4 of helix pitch) on the performances of axial overlap HBHXs with inclined angle of 40°, and the simulation results indicated that for the same mass flow rate, the heat transfer per unit area decreases with the decrease of baffle space. Gu et al. [28] studied the performances of axial separation electric heaters with small incline angle baffles that forming greater helical pitch to reduce manufacturing cost. Du et al. [29] numerically investigated the influence of five geometric parameters on the axial overlapped helical baffle heat exchangers by Taguchi method, and the results indicated that the overlap size should be given prior consideration. Dong et al. [30] compared five trisection helical baffles heat exchangers with diverse incline angles and baffle structures, and the performance analyses showed that the 10° scheme had a better heat transfer capability while higher pressure loss, in contrast, 20° scheme had the best comprehensive evaluation index in the studied scope. Yang et al. [31,32] investigated two-shell-pass continuous helical baffle heat exchangers with one pass in the concentric cylinder with segmental baffles and the other in the annular channel with the continuous helical baffles.

Because of the difficulties in applying helical baffles in the half cylindrical space, the existing schemes for countercurrent U-tube STHXs are dominantly segment baffle ones. Yang et al. [33] investigated the unilateral ladder type helical baffle heat exchangers (ULHBHXs) aiming to form a helical channel to replace the zigzag channel in the half cylindrical space for high-pressure feedwater heaters. The results proved that the average values of shell-side heat transfer coefficient raised 13.2–18.2% compared to the segmental ones and the results gave preliminary trends of geometric parameters of ULHBHXs on the performances.

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